NREL's ReFUEL Laboratory, Biodiesel Studies & Heavy Hybrid Program

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ReFUEL Test Facility

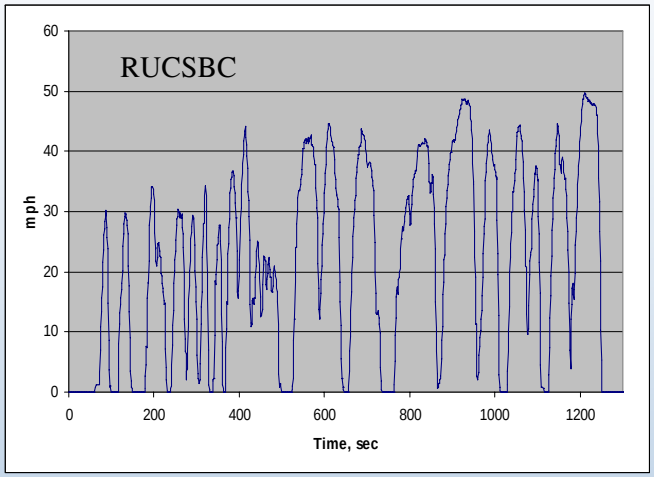
- Dedicated in July 2002
- Heavy-Duty Engine and Vehicle Test Lab
- Expertise in alternative fuel testing and heavy-hybrid vehicle testing
- Support Facility for NREL's CTTS

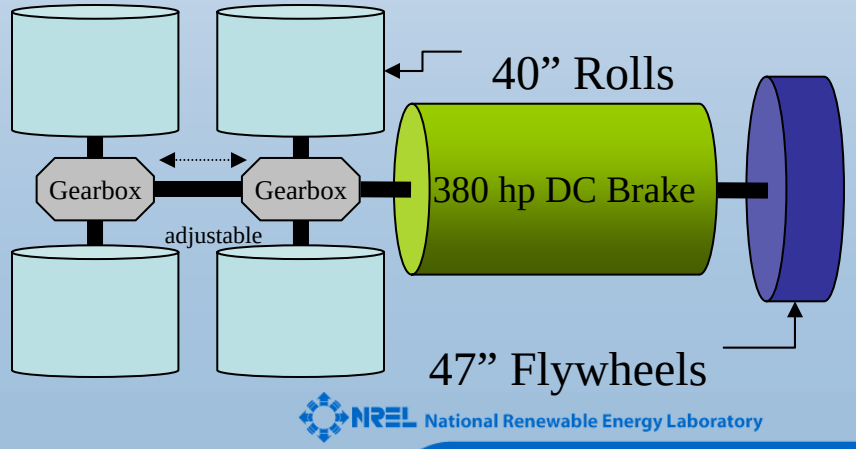
ReFUEL Engine Test Cell

- 400 hp (300kw) DC Dynamometer
  - 5000 rpm max. speed
  - AVL- Digalog Testmate controls – transient (FTP)
  - Programmable steady state modal testing
- Data Acquisition
  - 72 channels Analog I/O
  - 24 channel high speed data acquisition (in-cylinder pressure, needle lift)
- Emissions Measurement
  - High accuracy (+/- 0.5% reading) fuel metering
  - Regulated emissions measurement capability meets 2010 HD on-road req. (2007 CFR, including part 1065)
  - Metered and conditioned intake and dilution air
  - Flexible full-scale CVS system
  - 2010 level gravimetric PM measurement capability

ReFUEL Chassis Dynamometer

- Test Range: 8,000–80,000 lb (Class 3-8)
  - Twin 40” rolls (adjustable wheelbase)
  - 380 hp DC motor
- Features
  - Road load simulation
  - Electrical inertia simulation
  - Programmable driver’s aid
  - Augmented braking
  - Grade simulation
  - Automated warm-up & coast-downs
- Data Acquisition
  - 2010 level emissions measurement
  - 72 channels analog I/O
  - High accuracy (+/- 0.5% reading) inline fuel metering, mass and volume flow





ReFUEL Vehicle Testing











ReFUEL On-road Testing

- Portable Emissions Measurement System (PEMS)
- Continuous Measurement of CO, NO, NO2, THC, CO2 & O2
- Ambient temperature, relative humidity, global positioning satellite (GPS) receiver, vehicle interface
- Used in EPA on-road compliance testing

Biodiesel Emissions Studies

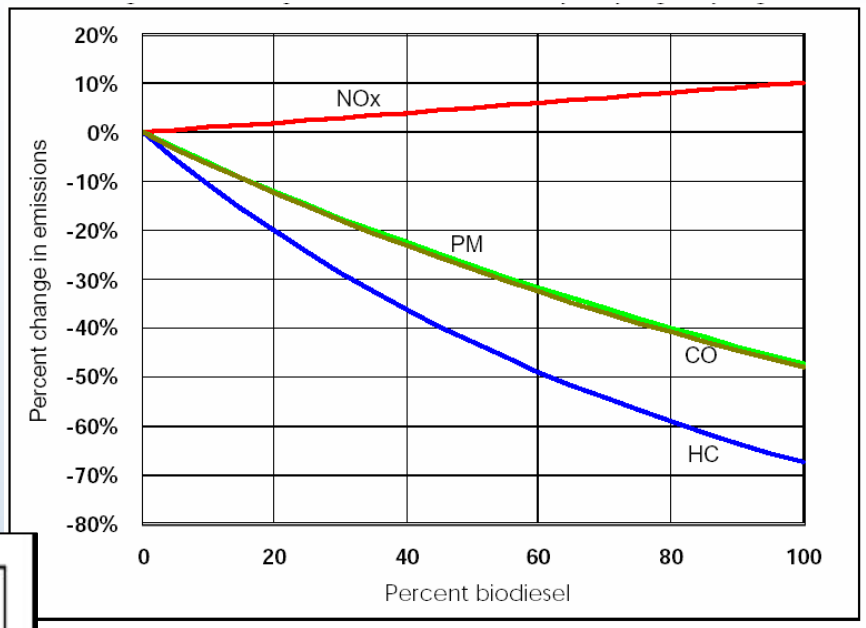
Biodiesel Aftertreatment Studies

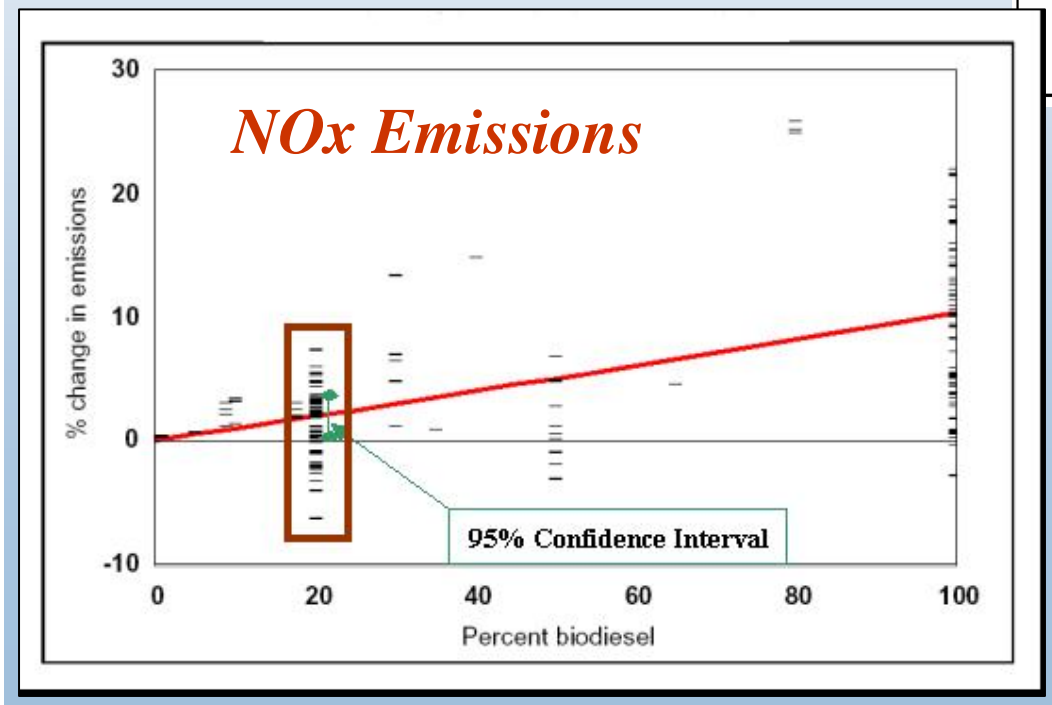
Biodiesel Fleet Evaluation Studies

Biodiesel Fuel Quality Studies

Emission Impact of B20

- 10% to 20% reduction in HC, PM and CO
- Impact dependent on engine, test cycle, and other factors
- Impact on NOx emissions less certain





- EPA review of published data found B20 causing NO_x to go up ~2%
- Many studies show NO_x going down with B20
- Data set was heavily weighted by one engine model

NREL's Literature Review of Recent Testing Results

Engine dyno results published since release of EPA review

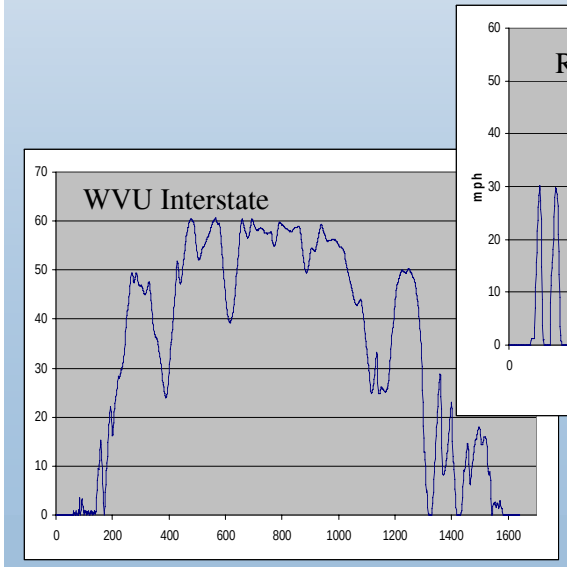
- NO_x ranges from -10% to +6%
- Average change in NO_x for B20 is -0.6%±2.0%
  - Change is not significantly different from zero

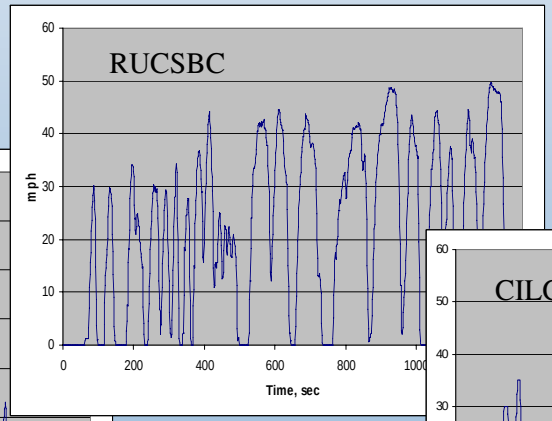
Chassis dyno results published since release of EPA review

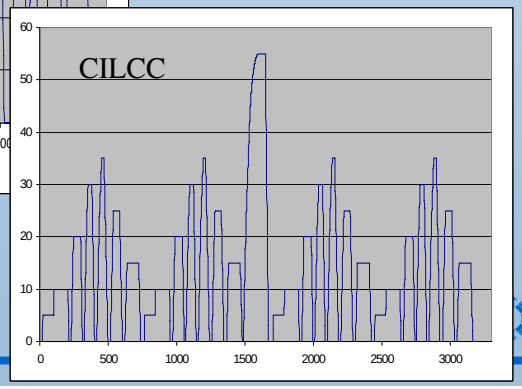
- NO_x ranges from -3% to +14%
- Average change in NO_x for B20 is 1.4%±4.5%
  - Change is not significantly different from zero

NREL Vehicle Testing Study

- 8 heavy-duty on-road vehicles
  - 3 transit busses, 2 school busses, 2 Class 8 Tractors, 1 motor coach
  - Engine MY 2000 through 2006
  - EGR, DOC and DPF technologies represented
- 5 representative drive cycles
  - CSHVC, Freeway, RUCSBC, WVU interstate, UDDS
- Test Fuels – ULSD, B20 (ULSD + Soy)







NREL Vehicle Testing Study

- Percent change in NO_x ranges from -5.8% to +6.2%
- Average change in NO_x is 0.6% ±1.8%

		Percent Change				
Vehicle	Cycle	NOx	PM	CO	THC	Fuel Economy
Transit Bus #1	CSHVC	-5.8	-17	-27	-28	-2.2
Transit Bus #2	CSHVC	-3.9	-33	-20	-28	-2
Transit Bus #3 (avg both)	CSHVC	-3.2	-19	-15	-24	-1.9
Freightliner Class 8	CSHVC	2.1	-19	-11	-15	-1.5
	Freeway	3.6	-26	-7	-16	-1.6
Motor Coach	CSHVC	2.8	-28	-22	-15	-1.3
	UDDS	3.4	-30	-19	-3	-0.6
International Class 8	CILCCmod	-0.1	-27	-15	-17	-2.3
	Freeway	2.3	-35	-15	-12	-0.5
Green Diesel School Bus	CSHVC	-0.8	*	*	*	-2
	RUCSBC	2.3	*	*	*	-0.8
Conventional School Bus	CSHVC	-0.7	3	10	-1	-1.1
	RUCSBC	6.2	-24	-23	-20	-0.3
	Average	0.6	-23	-15	-16	-1.4
	95%+/-	1.8	10.2	6.1	8.6	0.4

**Vehicle equipped with diesel particle filter, changes in PM, CO, and THC not statistically significant*

Summary – Biodiesel NO_x Impact

- NO_x can increase or decrease depending on engine
- Data compilations that are not weighted to one engine model show no change in NO_x on average for B20
- Additional research is needed to quantify impact
- Reduction in PM, CO, and THC is robust

These results have led EPA to make a more neutral statement about biodiesel's NOx impact (RFS Final Rule):

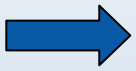
-Conclusion that NO_x increases not widely accepted

-Conflicting results from other studies

-Additional studies involving all stakeholders are planned

Effects of Biodiesel Blends on Vehicle Emissions:
http://www.nrel.gov/docs/fy07osti/40554.pdf

Biodiesel Emissions Studies



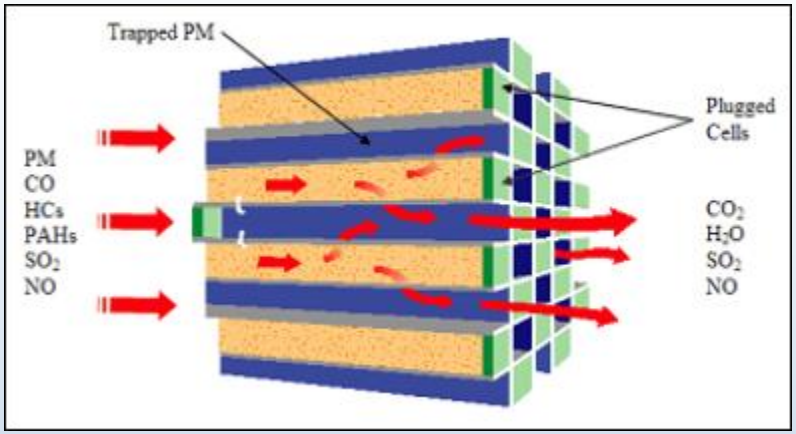
Biodiesel Aftertreatment Studies

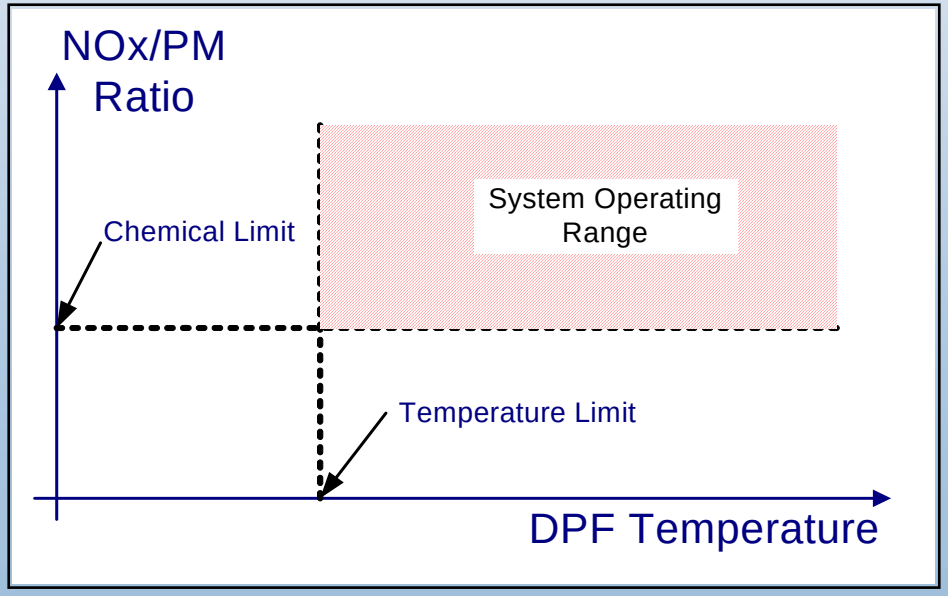
Biodiesel Fleet Evaluation Studies

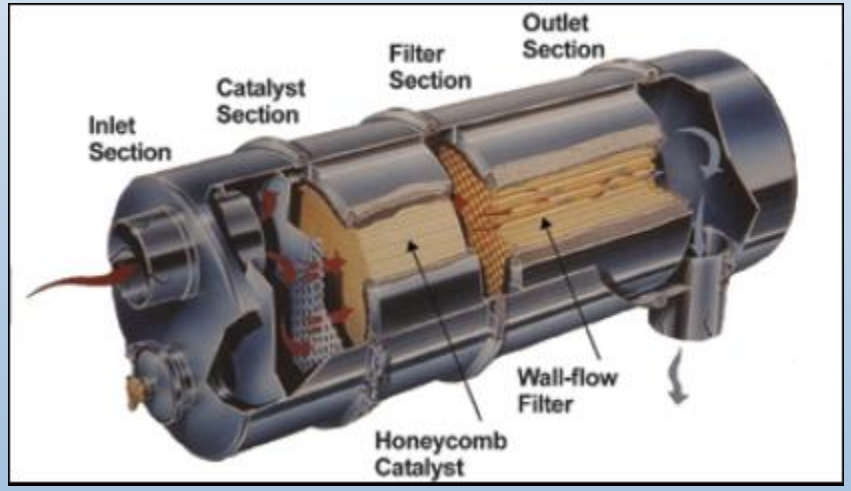
Biodiesel Fuel Quality Studies

Diesel Particulate Filters (2007 aftertreatment)

- Alternating plugged channels force flow through porous ceramic substrate
- At low temperatures PM is trapped
- At high temperatures trapped PM is oxidized with NO_2



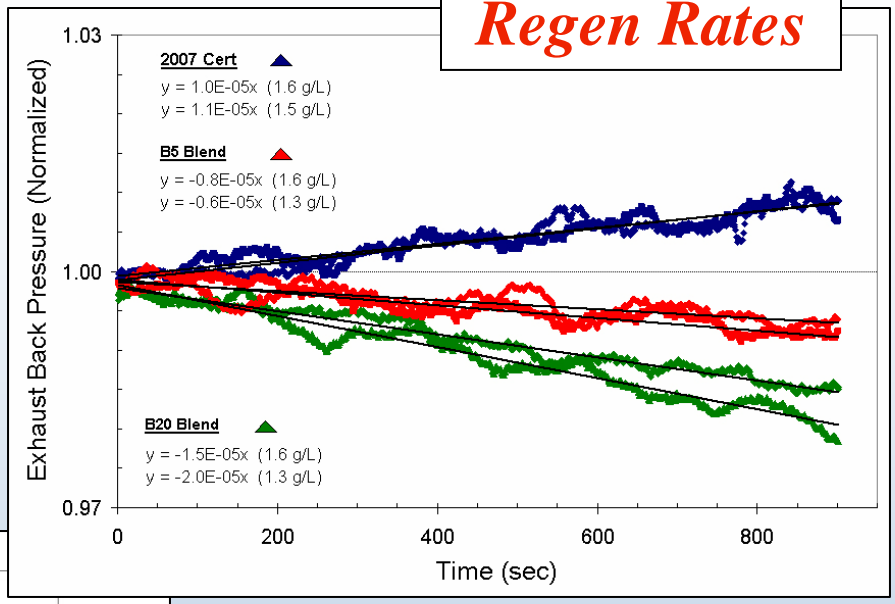




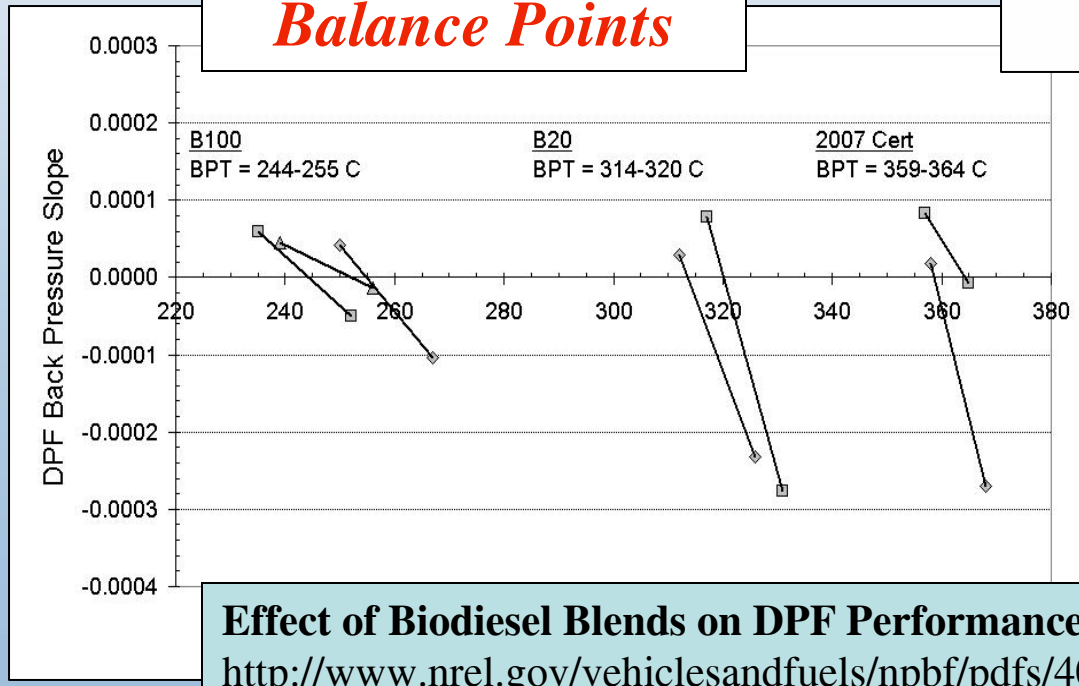
DPF Balance Point Temperature & Regeneration Rate

- DPF Regeneration Rate increases with increasing biodiesel content
- Even at 5% blend levels biodiesel PM measurably oxidizes more quickly

Regen Rates



Balance Points



- BPT – DPF temp where soot load rate is equal to soot regeneration rate
- BPT with B20 and B100 is lower than 2007 Cert by 45 ºC and 112 º C

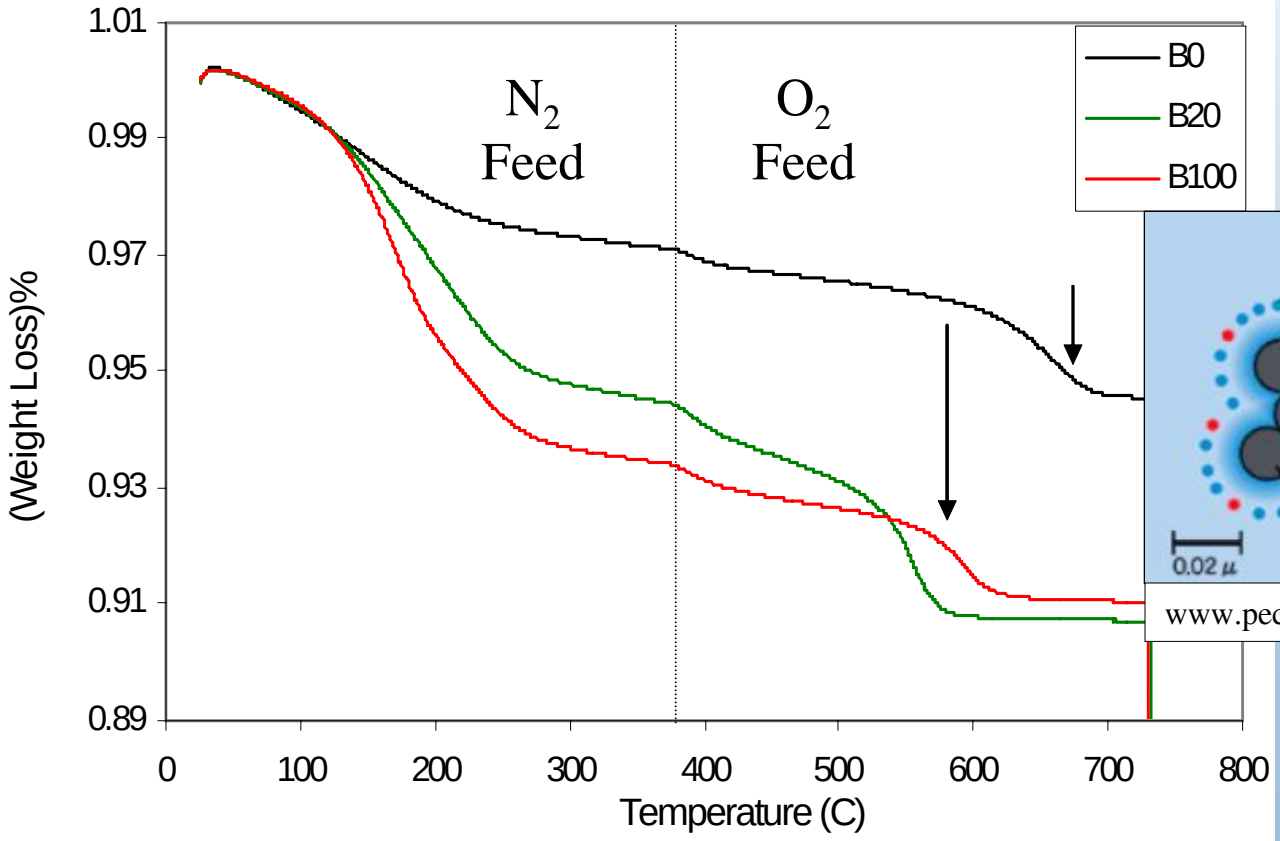
Effect of Biodiesel Blends on DPF Performance:
http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/40015.pdf

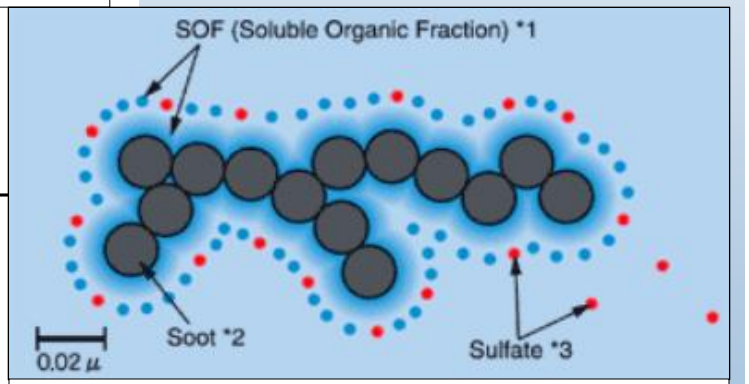
Biodiesel Soot Characterization

- Lower combustion temperature for biodiesel soot – (TGA)
- Higher disordered carbon content for B100 soot – G/D Carbon Ratio (Raman Spec)

  $G/D_{ULSD} = .836$ $G/D_{B100} = .586$
- Higher oxygen content for B100 soot – Carbon/Oxygen Ratio (SEM-EDX)

  $C/O_{ULSD} = 25.34$ $C/O_{B100} = 20.34$





www.pecj.or.jp/english/jcap/images/jcap18_01.gif

Biodiesel Emissions Studies

Biodiesel Aftertreatment Studies

→ **Biodiesel Fleet Evaluation Studies**

Biodiesel Fuel Quality Studies

100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends (B20)

- Compare vehicles operating in the field on B20 and conventional diesel over 24 months:
  - Engine performance
  - Fuel economy
  - Vehicle maintenance cost
  - Fuel-induced variations in operation and maintenance
  - Lube oil performance
  - Emissions

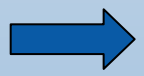
- 9 identical Denver RTD transit buses
  - 2000 Orion V; Cummins ISM
  - 5 operated on B20, 4 on Diesel
- Dedicated to fixed Route – identical duty cycle
- On-road fuel economy, road calls and overall maintenance costs – similar for both fuels

Proc, et al., "100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends (B20)" SAE 2006-01-3253

Biodiesel Emissions Studies

Biodiesel Aftertreatment Studies

Biodiesel Fleet Evaluation Studies



Biodiesel Fuel Quality Studies

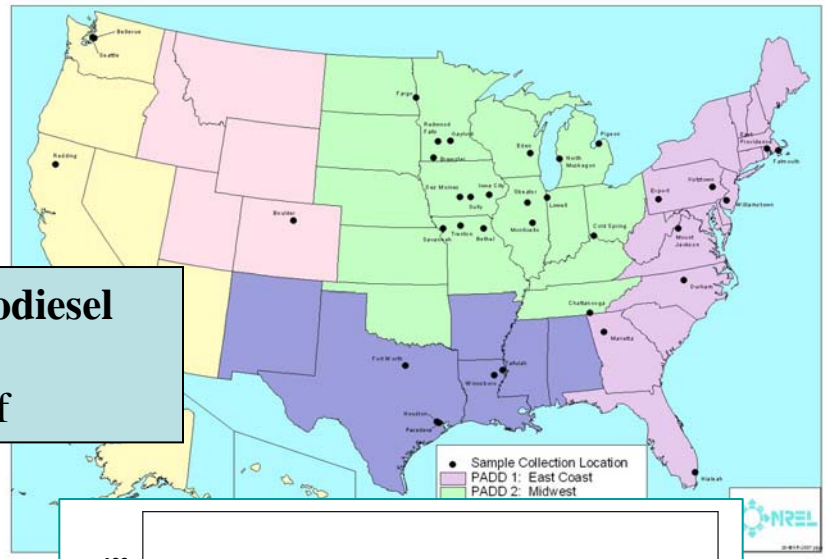
Potential Impurities in Biodiesel

- Methanol
  - Degrades some plastics and elastomers, corrosive
  - Can lower flashpoint to unsafe levels (fire safety)
- Unconverted/partly converted fat (bound glycerin)
  - Results in very poor cold flow properties, injector and in-cylinder deposits, potential engine failure
- Glycerin (free glycerin)
  - Results in injector deposits, clogged fuel filters, deposit at bottom of fuel storage tank
- Catalyst (caustic, NaOH)
  - Excessive injector, fuel pump, piston, and ring wear, filter plugging, issues with lubricant
- *All are limited by ASTM D6751 specification*

Biodiesel Quality Surveys

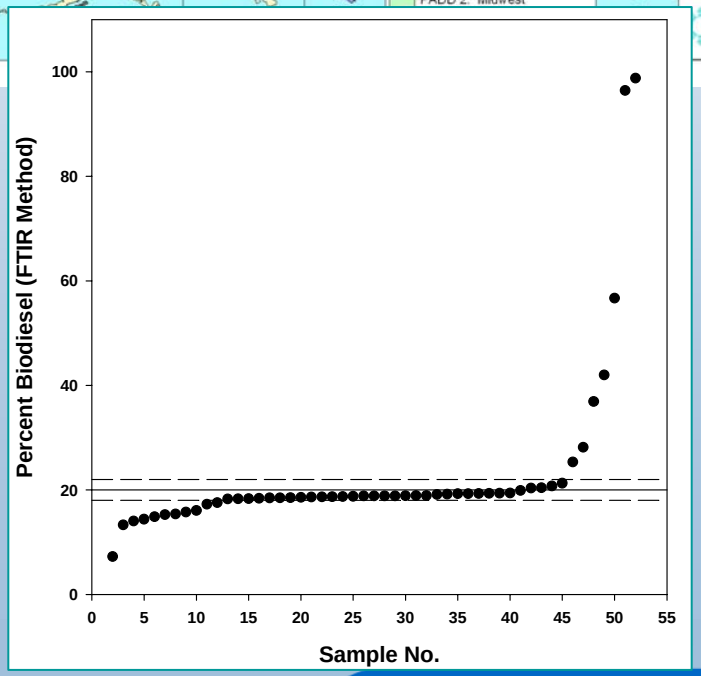
- B100 exhibited 15% failure rate in 2004
- Identified problems with consistent blending of B20 in 2004

Survey of the Quality and Stability of Biodiesel and Biodiesel Blends in the United States in 2004
http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/38836.pdf



- B100 exhibited 50% failure rate in 2006

2006 B100 Quality Survey Results: Milestone Report
http://www.nrel.gov/docs/fy07osti/41549.pdf



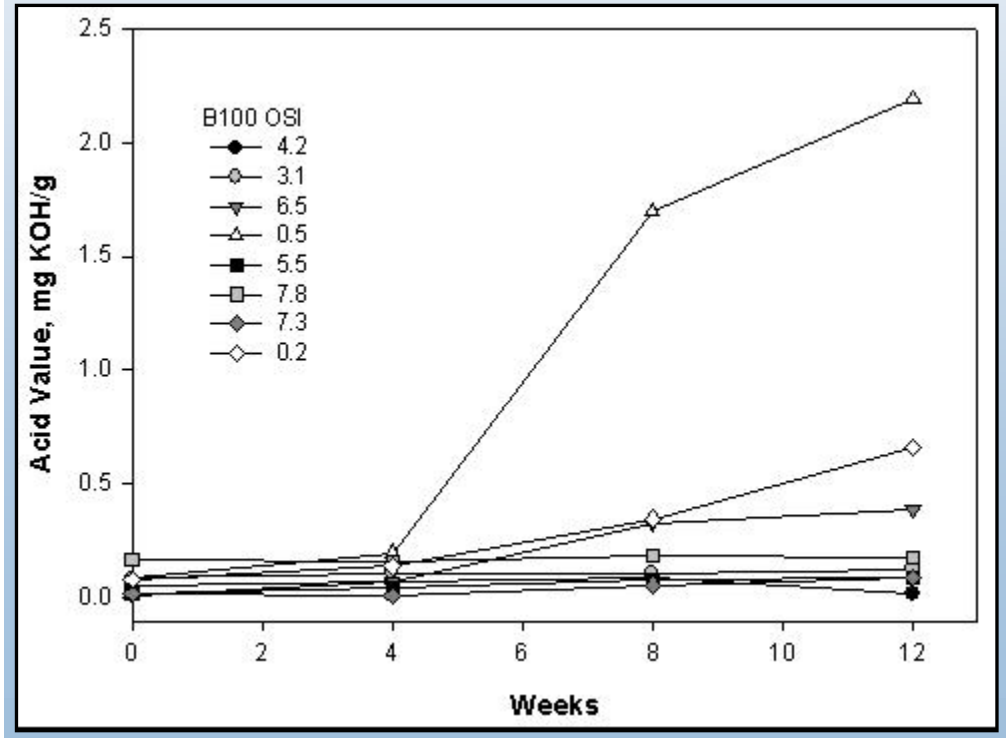
- Additional surveys ongoing
  - Surveys and education needed on a continuous basis

Biodiesel Degradation

- Microbial contamination
  - Biodiesel is biodegradable
  - Microbes form films or mats that can plug filters
  - Requires water in storage tank
  - Storage tank housekeeping issue/biocide treatment
  - Also an issue for petroleum fuels
- Oxidation
  - Increases acidity (limited in D6751 to 0.5)
  - Forms gums
  - A stability requirement is included in D6751

Biodiesel Stability Study

- NREL/NBB stability study shows that blend stability is dominated by B100 stability
- This work led directly to the adoption of a stability requirement for B100 by ASTM
  - 3 hour OSI induction time



"Cummins is able to upgrade its previous position on the use of biodiesel fuel, which limited the use to B5 blends only, up to B20 for three key reasons. First, the American Society of Testing Materials specification ASTM D6751 now includes an important stability specification for B100 biodiesel."
http://www.everytime.cummins.com/every/news/release99.jsp

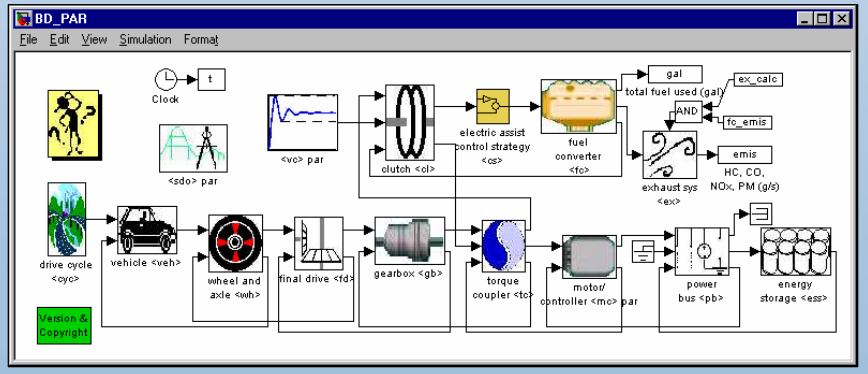
Empirical Study of the Stability of Biodiesel and Biodiesel Blends
http://www.nrel.gov/docs/fy07osti/41619.pdf

Advanced Heavy Hybrid Propulsion Systems (AHHPS) Program

- **Program Goal**
  - In coordination with 21st Century Truck Partnership, develop technology to enable up to a 100% increase in fuel efficiency in Class 3-8 heavy hybrid vehicles while meeting EPA 2007 emissions standards
- **Market Segment Focus**
  - Heavy-duty on-road commercial vehicles, not including line-haul Class 8 trucks
- **Benefit**
  - 250 million BBL/year projected savings in imported oil by 2020
- **Industry Cost-Share Partners**
  - Eaton/International Truck
  - Oshkosh
  - GM/Allison
  - Caterpillar

AHHPS Technology Focus

- Eliminate Technical Barriers, Reduce Costs, Improve Component and System Performance
  - Engine Technologies
  - Motor/Generator Technologies
  - Energy Storage Architectures & Systems
  - Power Electronics & Control Systems
  - Auxiliary Load Electrification
  - Waste Heat Recovery Systems
  - Propulsion System Architectures

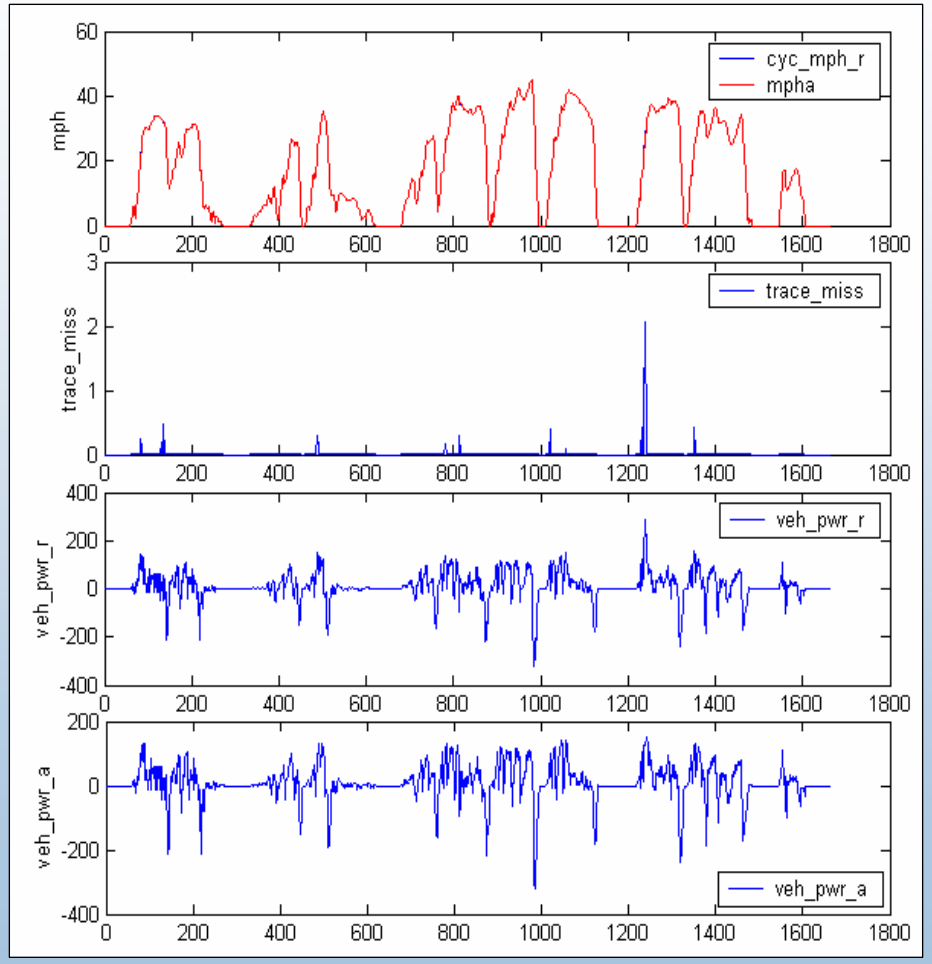


Barriers to Commercialization

- Initial & Life Cycle Component & System Costs
  - Cost Reduction Factors of 2-10 Are Commonly Required
- Component Reliability & Performance
  - Component & System Performance Cannot Compromise the Mission
  - Technology Maturation for Heavy Duty Market
  - Demanding Applications Require Higher Reliability & Durability
- Controls & Systems Integration
  - Hybrid Systems Must Operate Transparent to the Driver
- Certification & Emissions Testing

Major Challenges for Hybrid Designs

- Extreme Vehicle Diversity
  - Specialization for the customer's needs (designed for the job)
  - Many different vehicle weight classes, vocations & duty cycles
  - Wide range of drivetrain and accessory options
- Driving cycles and usage patterns vary greatly among vocations and customers
- Systems analysis and optimization is difficult
- Manufactures are challenged to achieve economy of scale



AHHPS Subcontracts

- **GM – Allison Transmission**
  - Heavy Hybrid Transit Bus Application & Prototype Validation
  - Advanced Parallel Hybrid Powertrain

King County Metro Transit: Allison Hybrid Electric Transit Bus Laboratory Testing
http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/39996.pdf

- **Eaton / International**
  - Class 4-6 Vehicle Applications & Prototype Validations
  - Advanced Parallel Hybrid Powertrain
  - Down-sized 3.0L I4 Diesel Engine
  - Auxiliary Load Electrification

- **Oshkosh**
  - Class 7-8 Vehicle Application & Prototype Validation
  - Advanced Series Hybrid Powertrain
  - Extremely Demanding Duty-cycle

- **Caterpillar, Inc.**
  - Focus on Thermoelectric Waste Heat Recovery
  - Several Hybrid Vehicle Applications

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